ANALYSIS OF 4-DOF FORCE/TORQUE SENSOR FOR INTELLIGENT GRIPPER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR DEGREE OF

Bachelor of Technology
In
Mechanical Engineering
By

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Roll No: 1O7ME028

Department of Mechanical Engineering
National Institute of Technology
Rourkela
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Under the Guidance of

Prof. B. B. Biswal

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ROURKELA

CERTIFICATE

This is to certify that the thesis entitled, "**ANALYSIS OF 4 DOF FORCE/TORQUE SENSOR FOR INDUSTRIAL GRIPPERS.**" submitted by **VINAY GANTI** in partial fulfillment of the requirements for the award of Bachelor of Technology in **Mechanical Engineering** at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any Degree or Diploma.

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I take this opportunity to express my sincere thanks to my project guide for co-operation and to reach a satisfactory conclusion.

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ABSTRACT

This paper describes the development of a six-axis gripper force sensor that measure forces f_x, f_y *and* f_z and M_x, M_y *and* M_z simultaneously, and the intelligent gripper will be using the six-axis sensor for grasping or holding any object with the force calculated. To grasp any object of unknown dimensions and weight by using an intelligent gripper safely the forces are to be calculated along the gripping direction and gravitational direction, and perform the force control with the measured forces. Thus, the intelligent gripper should be composed of six-axis gripper force sensor that measure forces f_x, f_y *and* f_z *and* M_x, M_y *and* M_z at the same time. In this paper, a six-axis gripper force sensor for measuring forces f_x, f_y *and* f_z and M_x, M_y *and* M_z simultaneously were newly modeled using 16 strain gauges. The structure of a six-axis wrist force/moment sensor was modeled for an intelligent hand in robot newly. And the sensing elements of it were designed by using FEM design system ANSYS. All along the way the stress points are found out where max. And min. stresses are applicable and the design of sensor is done so.

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CHAPTER 1

INTRODUCTION

INTRODUCTION:

Industrial robots play a vital role in the industrial applications. There are many kinds of industrial robots that we come across when we look into the industrial uses. Among these robots we see even humanoid robots coming across. For these humanoid robots the grippers are in the form of hands. And these hands are categorized into two. 1. Modular hands and 2. Integrated hands.

Now the hands will be having sensors at different locations for the evaluation of force and moment. Many type of sensors are found in the hand namely potentiometer in the joints, rotary transducers in the motors, 6-axis force –torque sensor at the finger tips and torque/moment sensors in each joint.

Introduction of Information Technology in the arena of automation brought a revolution here. It has boosted the industrial automation as the performance of intensity was multiplied by control technology and the processing done by the sensor data. Force sensors are mainly used in the gripper hands for the sensing of the force that would be applied upon the object it will lift from which the load of the item/object is sensed. The most used are the transducers with strain gauges, known as load cells that have as main mechanical component an elastic element. Although there exist several different types of multi-dimensional force sensors, Lorenze et al pointed out that most of the conventional force sensors are not suitable for using in robotic systems. Hence these kinds of sensors are suggested and research is being done in the field. Here, we go with the 6-axis force sensors which will be measuring the forces/moments along the 6-axis $f_x,\ f_y\ and\ f_z\ and\ M_x,\ M_y\ and\ \ M_z$. Here the moments are $M_x, M_y\ and\ M_z$ and forces are $f_x, f_y\ and\ f_z$ along the 3 respective axes X, Y and Z.

There are many sensing elements such as PPB’s (parallel plate beams) and SG’s (strain gauges). Here the work is done with the strain gauge as the sensing element. Sensor will be having the dimensions as 58 x 58 x 12 mm. Here the geometry and physical properties of the transducer then fully define the static and dynamic response, and therefore the sensitivity and the bandwidth. For example, take the case of simple cantilever beam where the force applied at the end will be resulting in the thereby can be converted into force from the calibration that is predetermined. When the strain gauges are arranged such that it a Wheatstone's bridge. A force sensor is a device that transforms the measuring quantity variation in an electrical signal, usually a voltage variation to the required force. Here we present the mechanical structure of sensor and it is designed and the strain is analyzed in FEM software ANSYS. Then the max. Stress and min. stress points are pointed in the meshed figure. There after the deflections in the beams due to the forces and torques acting along the beams are found and the variations of stress along the beams are graphs are plotted.

CHAPTER 2

LITERATURE REVIEW

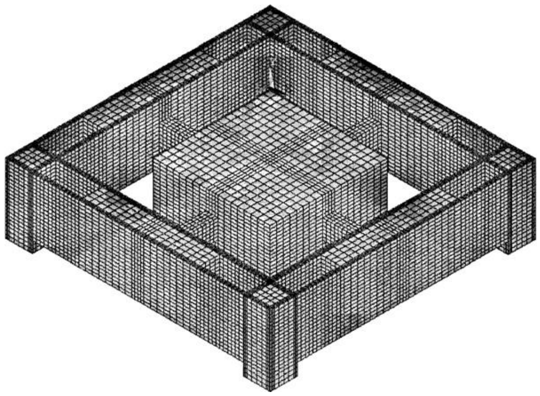
LITERATURE REVIEW

Scientists are working on the development of an intelligent robot as because people want to get a mechanism that would help and work for the human being. In order to get a mechanism that is similar to human hand, the sensors are mounted on the gripper or hand of the intelligent robot for calculating the forces $f_x, f_y\ and\ f_z\ and$ moments $M_x, M_y\ and\ M_z$ simultaneously along the X, Y and Z direction respectively. The sensor is used to accurately measure the weight of the object lifted, pushing and pulling of the sensor done by the 3 forces and 3 moments properly.

Kim [2] has developed a multi-axis force/moment sensor with a less interference error of less than 3% but cannot be mounted on the robot hand fingers because of its improper size and shape. The sensing elements are found with the disadvantages that the design has become complicated with various rated loads and outputs. The United States and Japan have already designed many kind of multi axis force sensors with the drawbacks that the cost in so high and are unable of mounting them on the special intelligent grippers hand.

Thus it has become necessary to develop a six axis force/moment sensor with a new structure such that it gets suited on the intelligent robot's hand. Hence a 6 axis force/moment sensor sensing $f_x,\ f_y\ \ and\ f_z\ and\ M_x,\ M_y\ and\ \ M_z$ is developed with a low interference error are to be designed and fabricated. It should be taken care while designing and fabrication such that the interference error will be less than 3% and for proper rated load, output.

Then the research took the development all the way to design a sensor with PPB's and rectangular beams on which the sensing elements are mounted. The design variables of the force/moment sensor are size of the body, output of each sensor and rated load. After the design is accomplished the strain gauges mounted on the sensing elements in such way that it forms a Wheatstone's bridge. Due to the stress upon the sensing elements its resistance will have a change causing a deflection in the voltage whereby we can find the strain output on each of the sensor. The structure of the sensor and its deflection are shown in the fig. 2.1 and 2.2.



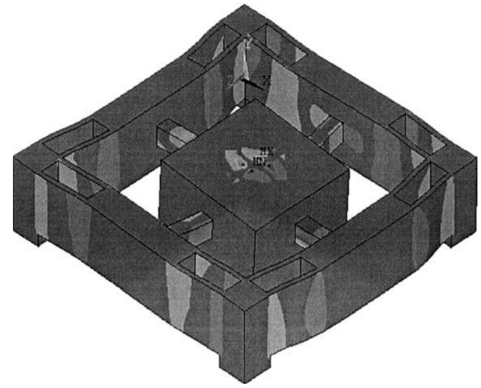


Fig.2.1 Finite element mesh for FEM analysis sensor under force of six-axis wrist force/moment Sensor in three-dimension.

Fig. 2.2 Deformed shape of six-axis wrist force/moment $f_x$and f_y

Once after the design is done along with the analysis in ANSYS it is found that the error is more at the ends of the beam because of the numerical error in the ANSYS software. Then the practical experiments are made to get the results out. From there the errors are found out between the practical results and designed results.

Multi-axis force sensors to detect the resultant force and moment vector applied to a robot finger are useful for controlling the grasping force of the robot hand and for contact sensing with objects [9][10]. Here it is dealt with the design and analysis of 3 axis tactile forces sensing along with slip sensing. Initially a prototype sensor is constructed that consists three tactile heads which are 6mm apart. Beneath each tactile head, three pressure transducers are induced for the flexible polyamide film. Principle of tactile pressure transducer is so simple. Principle involved here is pressure-optical conversion technique, where due to the pressure the change in the area is found. The first and last layers are in hertzian contact here. Here due to the application of pressure or force the resistance between the nib and the resistive film, a change in resistance is found. A full bridge circuit for the tactile head is formed and advantageous in temperature compensation. These bridge connections are made for high sensitivity and temperature compensation.

Structure of the sensor:

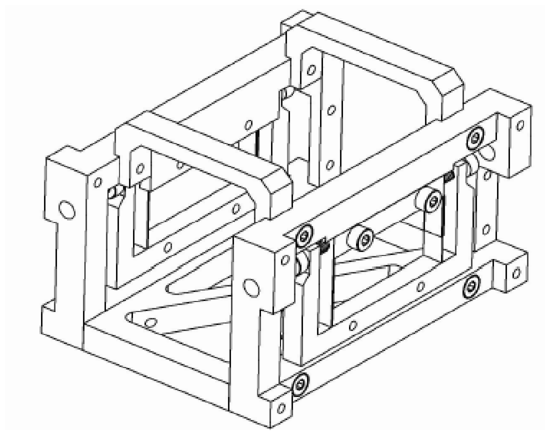


Fig. 2.3 Force Sensing Structure

This fig. 2.3 shows the force sensing structure, it's a proposed structure of the sensor. Here the structure is selected such that the flexible thin beams are supporting. Here the vertical beams will be subjected to strain. Their dimensioning allows them to deflect primarily in the insertion direction and be relatively resistant to off axis forces [3].

Dimensioning the flexible beams:

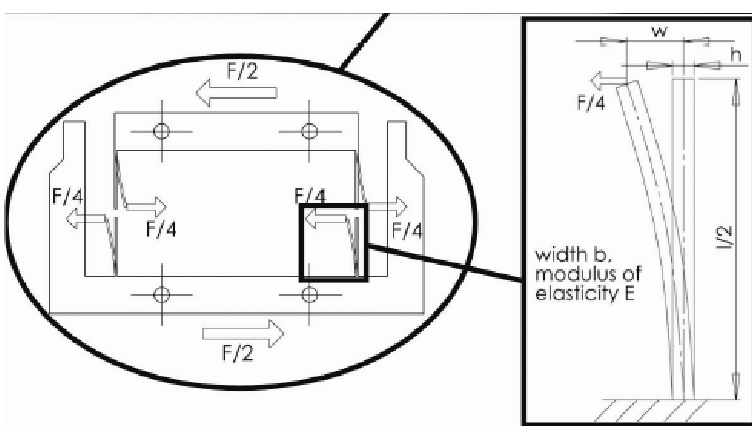


Fig. 2.4 Deflection of the beams on the application of stress on which strain gauges are mounted

Core units are the flexible units for the housing as showing in fig. 2.4. As there are two parts in the insertion mechanism (one on each side) the force will be divided into two equal halves leaving F/2 on each of the part and on the every part (having length l, height h, width b) there are two vertical beams which will further reduce the force into half of the previous force making it F/4 on every strain gauge. Here the height (h) should be comparatively small to the width (b) for increasing the torsional rigidity and lateral stiffness. To limit the maximum deflection 2 limit screws are arranged on the each side which set the larger deflection of upright posts in fig. 2.3 & 2.4 [3]. In order to the over stressing on the elastic beams of thin force, these are the mechanism for achieving the prevention of over stress or reduction of over stress. The forces on each of the 4 beams is $F_B = Mg/4$.

CHAPTER 3

STRAIN GAUGES

3.1 Strain and stress:

When an object is subjected to external forces stress and strain are the outputs. Stress is the resultant of internal resisting forces and strain can be defined as the deformation and displacement occurred in the object due the external forces.

$$\text{Stress } (\sigma) = F/A$$

Strain is the amount of the deformation or displacement per unit length when a load is applied on an object. Hence strain can be calculated by dividing the deformation length in the object to the original length.

$$\text{Strain } (\varepsilon) = (\Delta L)/L$$

These strains may be compressive or tensile, can be measured by the strain gauges. Lord Kelvin in the year 1856 found for the first time that mechanical conductors when subjected to strain will exhibit a resistance change. There after the research is put on in after 1930. Basically any strain gauge is designed to convert the mechanical strain that it is subjected to into an electrical signal.

Principle on which strain gauge works: Change in the capacitance, inductance or resistance will be proportional to the strain that sensor is experienced to. When the wire is subjected to tension, its length increases causing reduction in the cross-sectional area. This changes the resistance (R) in proportional to the strain sensitivity (S) of wire. This strain sensitivity or gauge factor (GS) will be given by the formula

$$GF = (\Delta R/R)/(\Delta L/L) = (\Delta R/R)/\text{ Strain}$$

Shearing strain considers the angular distortion of an object when it is subjected to stress. Consider when a force is acting on the surface of a book making it look like a trapezoid.

The shearing strain will be the tangent of the angel that it will subtend with the Y axis.

Poisson's ratio: The ratio of longitudinal strain to the lateral strain. When the longitudinal length is increased it will decrease the area causing the increase in the electrical resistance of the wire.

From many years strain gauges have been used as the basic sensing element for vast applications like pressure sensors, load cells, force sensors and position sensors etc.

Majority of strain gauges are foil types, available in many shapes and sizes for various applications. Here it contains series of pattern of resistive foils that are mounted on backing material. They work on the principle that when it is subjected to stress, resistance will change in a certain way. Strain gauge will be as shown in the fig. 3.1.

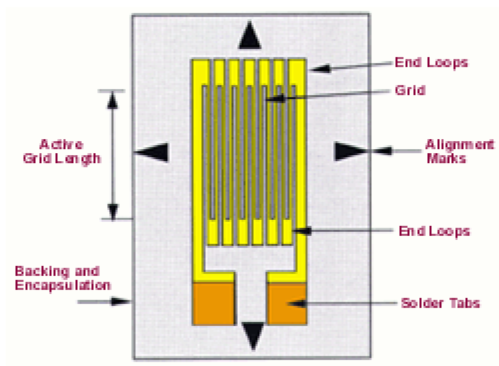


Fig. 3.1 Strain gauge foil

The strain gauges are so connected forming Wheatstone's bridge connection with the four strain gauges (full bridge), two gauges (half bridge) and single gauge (Quarter Bridge).

Conductive material strip is stretched, then it will become longer and skinner, both causing the increase of electrical resistance end-to-end. If the same metal strip is subjected to compressive stress within the buckling load, there will be broadening of the area and reduction in the length. If these stresses are within the elastic limit of the metal strip they will act as measuring element, evaluating the physical force. Such a device is called as strain gauge, and these strain gauges are used in day to day life measuring the stresses by machinery. Aircraft component testing is one area of application.

3.2 Wheatstone's bridge

Principle: In the Wheatstone's bridge when the resistances ratio is equal, there won't be any voltage variation. Else, by unbalancing the two legs of the Wheatstone's bridge there will be deviation in the voltage causing current flow. It is similar to the basic potentiometer. Wheatstone bridge is shown in the fig. 3.2

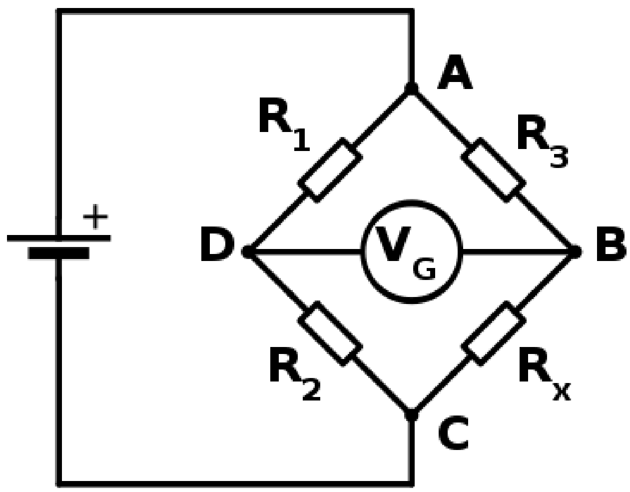


Fig. 3.2Wheatstone's bridge

Here in the Wheatstone's bridge the strain gauges will be placed in some of the slots of the 4 in the 2 legs of the bridge. By the application of the force on the strain gauges, the stress caused will change the resistance accordingly. Change in the resistance of the gauges will unbalance the bridge causing the deviation in the voltage which thereby causes the change in the current and finally the strain is evaluated. Before deformation, the strain gauge alignment in bridge is as shown in the fig. 3.3.

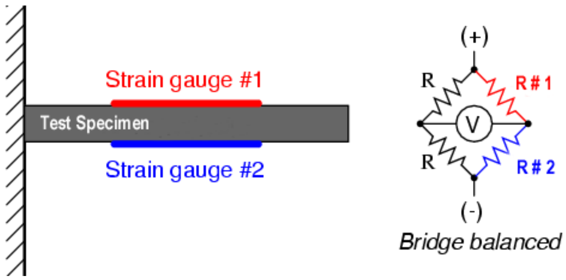


Fig 3.3 Balanced Wheatstone's bridge

When no forces are applied on the specimen the bridge will be balanced, and when the force is applied along the downward direction causing the bending of the specimen, resistances of the gauges will change simultaneously stretching gauge #1 and compressing gauge #2 of which the bridge gets unbalanced, hence the deflection in voltage and current passing through the circuit. The deformation can be seen in the fig. 3.4

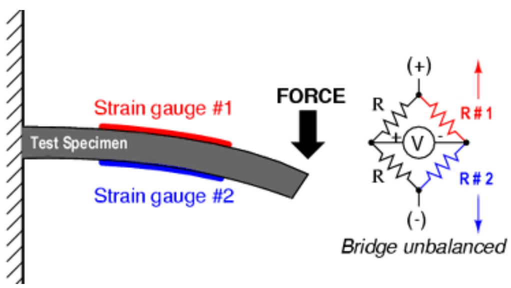


Fig 3.4 Unbalanced Wheatstone's bridge

CHAPTER 4

FORCE SENSOR STRUCTURE

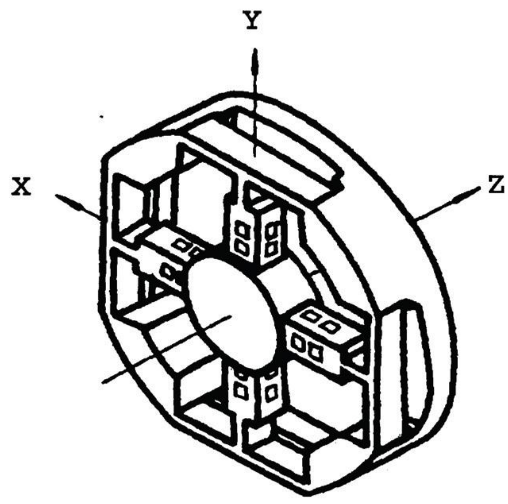
4.1Defining Problem Statement:

"Analysis of 4-dof force/torque sensor for industrial gripper with strain gauges as sensing elements."

It is now required to design a 4-axis force sensor with strain gauges as the sensing element. First and the foremost thing to be done here are defining the possible structure how a sensor could be and the places where the strain gauges has to be adhered for the stress and strain analysis. Because of the difficulty that would occur in mechanical design and motor control for Haptic Human Computer Interaction systems for 6 DOF feedback force, most of the HapHCI systems are using only 3 DOF feedback force. Sometimes uni-directional torque is also added, because of the feasibility of translation motion in 3 directions and rotational motion in 3 directions.

Hence, inspite of calculating the 6 force/moment information, it is constrained to 4 force/moment information by calculating the forces $f_x, f_y\ and\ f_z$ and the momentM_z. From this we can conclude that 4 force/moment $f_x,\ f_y,\ f_z$ and M_z are sufficient for the design of the sensor.

Multi axes force sensors for commercial use will typically measure all forces and moments. For this commercial 6 DOF force sensor, at least a total of 32 strain gauges are required which is shown in the fig. These strain gauges will be struck to the cross elastic beams of the sensor mechanical structure. Because of the difficulty that will encounter in attaching the strain gauges accurately and precisely at the respective positions where they are supposed to, the no. of DOF has to be constrained to 4 DOF. Another problem that will be encountering is coupled interference or noise among the 6 axis, which further will result in the complications in calibration. Alignment of gauges is shown in the fig. 4.1



Fig, 4.1. Mechanical structure of 6 DOF force/torque sensor

4.2 A New mechanical structure for force/torque sensor

Here it was developed a novel mechanical structure for 6 DOF wrist force/moment sensors before 1993 [Haung et al]. Because of some drawbacks and difficulties that are faced in calibration, it has been developed a new mechanical structure with four DOF force/moments.

The elastic body of the sensor mechanical structure comprises of central support beam, cross elastic beams, compliant beams and base of the body. Here the cross elastic beams are composed of 4 horizontal beams that are symmetrically arranged to the central support beam. The four compliant beams are connected vertically to the horizontal beams or cross elastic beams and the bottom of the compliant beams are connected to the base or the ring. It is shown in the fig. 4.2.

Whole design is made monolithic and symmetrical, so that the mechanical structure of 4 DOF force/moments sensors is simple and light.

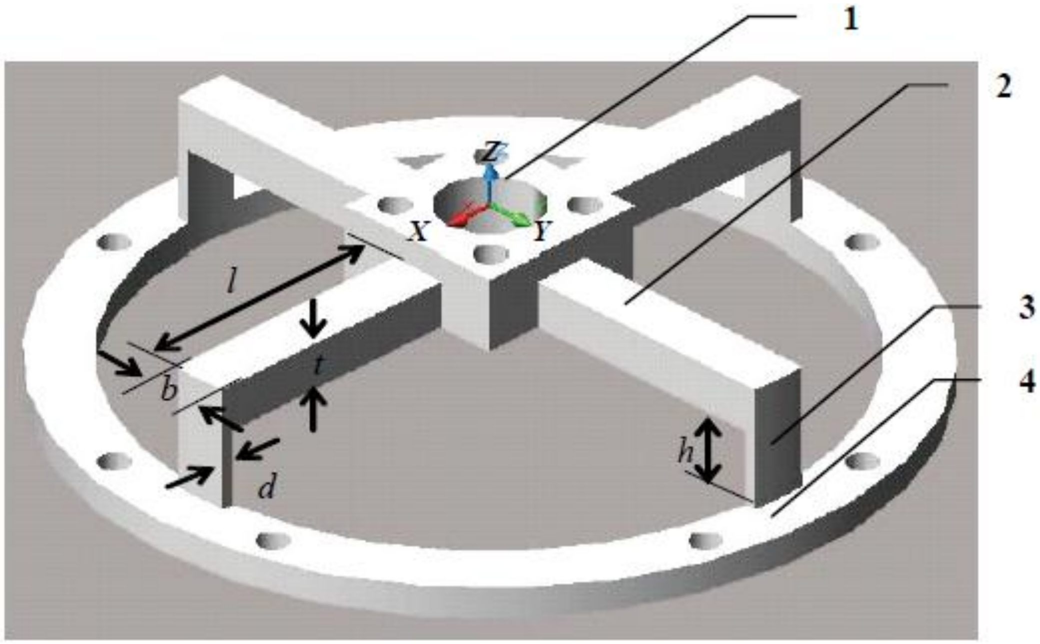


Fig. 4.2. The mechanical structure for novel force/torque sensor. (1) Center support of the elastic body, (2) cross elastic beam, (3) compliance beam, (4) base of the elastic body.

Here l, b, t are the length, width and thickness of the horizontal beam respectively. H, d are the height and thickness of the vertical compliant beam respectively as its width will be equal to the width of cross elastic beam and d $\leq \frac{b}{3}$.

4.3 Strain Analysis Theory:

Some assumptions are to be made before analysis, they are

(a) Stiffness of the elastic body designed should be strong enough to take the loads and moments. Forces applied are within the elastic limit so that the deformation occurred can be retained back after the removal of force.

(b) Strain gauges are adhered correctly, symmetrically and stably.

(c) Every line of component force passes through the center of the elastic body [1].

Figure 4.3 shows the skeleton of the 6 axes force/moment sensor with 4 DOF. When a single force Fx in the x-direction is applied, the two beams OA and OC float owing to the vertical beams AA' and CC' which act as compliant beams, while the other 2 cross sectional beams OB and OD becomes freely supported beams producing bending deformation owing to the vertical beams BB' and DD' which act as rigid beams. [1]

If the force is applied along Y direction F_y, then the beams OA and OC will possess the deflection of bending and are freely supported beams.

In case if the force is applied along the Z direction F_z through its center, horizontal OA and OC along with the other horizontal beams OB and OD will become freely supported beams producing equal bending deformation.

Likewise if the bending moment M_z is applied to the elastic body, the bending moment deformation will be same in all the 4 horizontal beams which are freely supported beams.

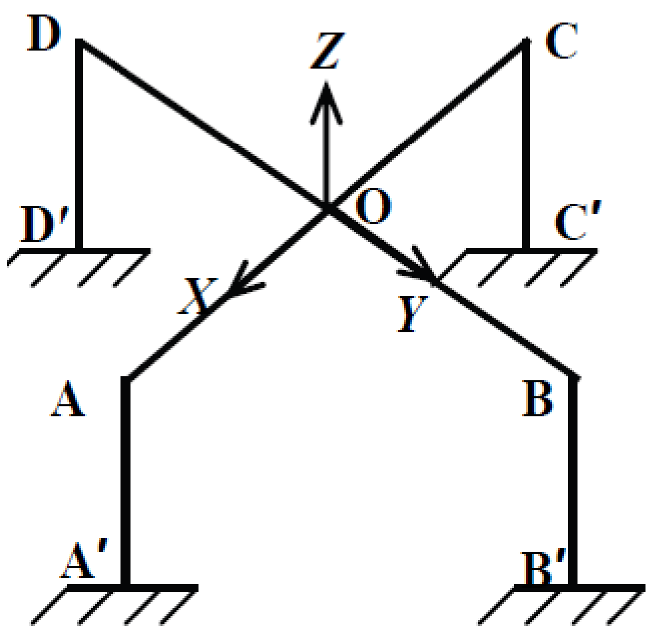


Fig. 4.3. The skeleton drawing of the sensor

For the novel, 4 DOF force/torque sensor only 16 strain gauges are enough for measuring the 3 axes forces and one axis torque, which is less than that of 6 DOF force/torque sensor. Hence the adhering of the strain gauges will be easier and can be accurately placed. Fig 4.4 shows the skeleton of the strain gauges arrangement on the cross elastic beams of the sensor.

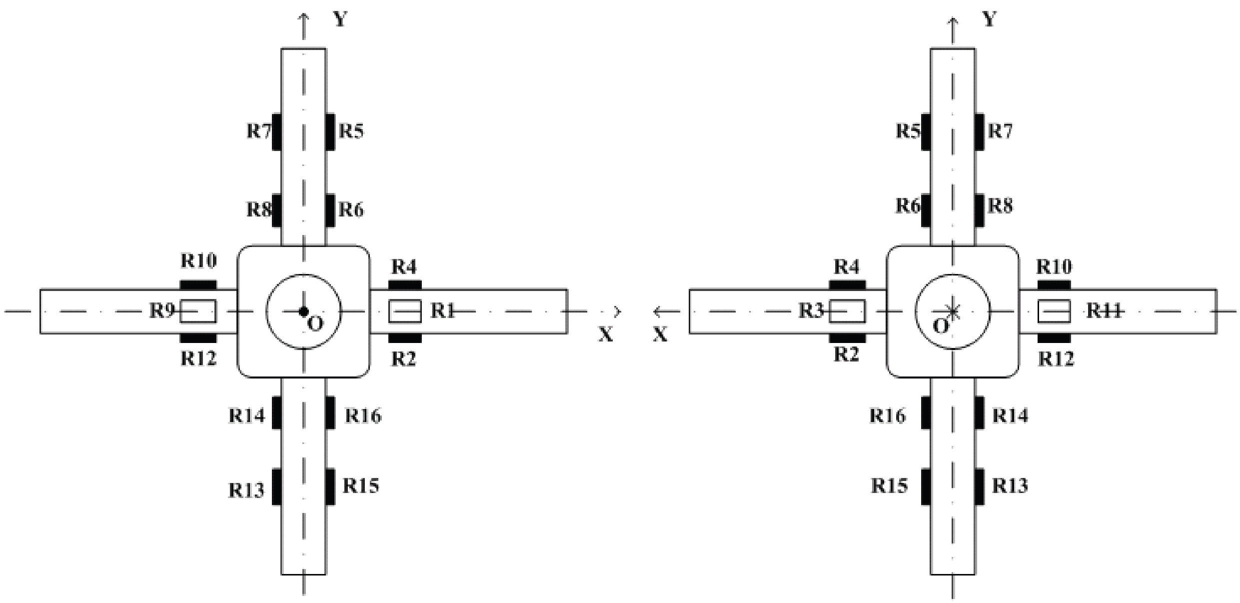


Fig. 4.4. Distribution of 16 strain gauges on the cross elastic beams.

Assuming the results of the 16 strain gauges R1, R2, R3 …. R16 as S1, S2, S3….. S16, we get a relation between 16 strain gauges and the each of the 6 axis force/torque sensor by using the theory of mechanism of material [1].

The 16 strain gauges are arranged into 4 full Wheatstone's bridge for calculating the 4 axes force/torque respectively as shown in the fig. 4.5.

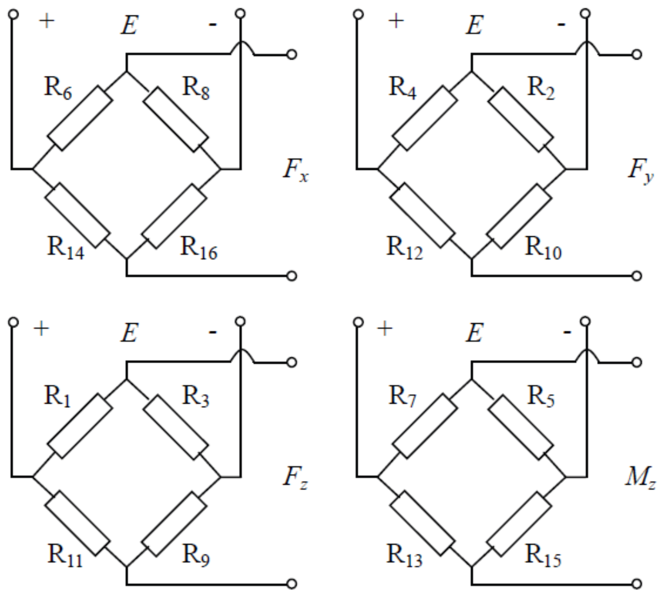


Fig. 4.5 Four Wheatstone Bridge circuits for four axes force/torque measurement.

Here ‘E’ is the voltage supplied by the power supply.
In reference [Haung, 1993] it is proved an important case of strain gauge output if a strain gauge is glued at the neutral axis of the beam, where the bending moment is acting in its flank, there won’t be any change or deviation in the strain gauge output as shown in fig. 4.6 [1].

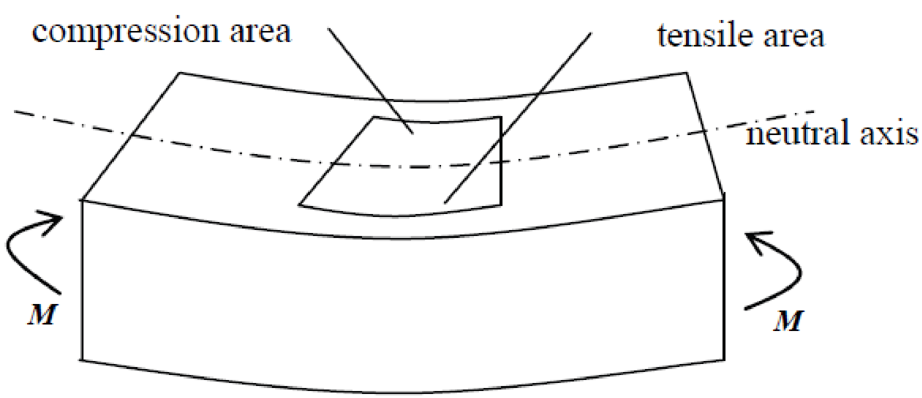


Fig. 4.6 The beam is under bending moment in its flank.

Here, another important case about strain gauge output can be proved easily. When the bending moment of the beam is acting around its central axis, the output of the strain gauges that are on the sides will increase due to the increase in the size of the strain gauge as shown in fig. 4.7.

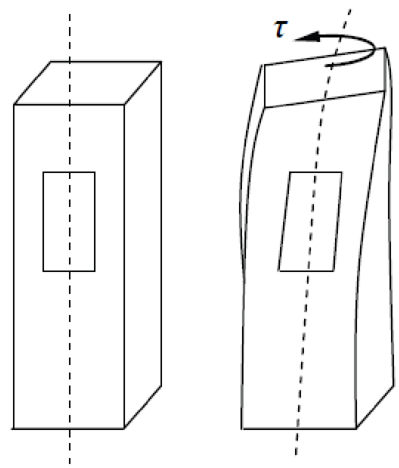


Fig. 4.7. The beam is under torque and moment.

4.4 Coupled Interference analysis by using finite element method:

Finite element analysis method, name itself implies that it is used for the minute and finite analysis of elastic bodies. The commercial software of FEM analysis ANSYS produced by the ANSYS corporation, USA, can be used for the analysis of the elastic bodies coupled interference with ease.

4.5 Finite element model of the elastic body:

First and the foremost step of the series of steps to be followed here is discretization of the domain to sub-regions. This sub division is also called meshing operation. Here we get many no. of sub domains called elements. The discretization of the decision as to the element number, size and shape of sub regions used to model the real body [1].

Discretization of the elastic body of 4 DOF force/torque sensor we use into sub regions is done by using the ANSYS software. Elements that we get here are set as SOLID 95, which is high precision element available in the ANSYS software. As we have to analyze the bending and the twisting of the beam here, this element will suit perfect for doing the act. Smart size function of ANSYS is used for the mesh generation control.

Total no. of element nodes after meshing is done is 48424 and elements are 27286. Fig. 4.8 shows the meshing diagram of sensor structure.

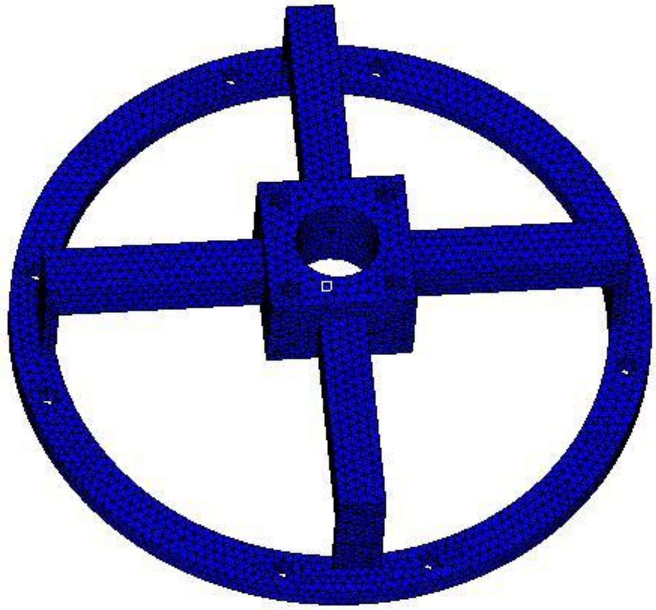


Fig. 4.8. Meshing structure of the sensor

Material that is used for the elastic body is aluminium. Its parameters are

Young's Modulus	$72\text{x}10^{9}$ pa
Poisson Ratio	0.33
Density	$2.78\text{x}10^{3}$ kg/m^{3}

Table 1. Parameters of elastic body material

4.6 Dimensions of the elastic body of the mechanical structure:

parameters	Cross Elastic Beam	Compliant Beam	Central Supported Beam
Length(mm)	l=21	h=7	14
Width(mm)	b=4.5	b=4.5	14
Height(mm)	t=4.5	d=4.5	9.5

Table2. Size of elastic body

4.7 Strain analysis under 6 axes force/torques:

(1) The boundary condition set

The elastic body is fixed to the base by the 8 bolts through the eight holes that are made on the base of the elastic body, so that the body is considered as a rigid connection for the application of load. Hence by the degree of freedom of elastic body's base is set to zero.

(2) Applied forces and torques

Each of the forces and torques are applied through the center of the beams respectively. The deformation of the all the beams due to each force and torque can be calculated by the use of ANSYS software. For the 16 strain gauges stuck to the beams, the outputs can be calculated by using the ANSYS software using the node operation. Total 16 nodes where these gauges are placed can be found and hence the strain at those points due to the forces and torques are out. They can be named as S1, S2….. S16 for 16 gauges respectively. The values will be +'s and –'s indicating the tensile and compression forces on the gauges respectively.

(3)Here we apply only 20N force along all the 3 axes and 20x4.5 N-m torque along other 3 axes. As we have constrained them to 4 DOF calculatingf_x, f_y, f_z $and\ moment\ M_z$. But the deflections in the beams will be same for both f_x and f_y because of the structure being symmetrical. Hence one of the forces of f_x and f_y is applied and the deflections in the beams are found out. Hence applied forces/torques are F_x = 20N, F_z= 20N and M_z= 20x4.5 N-m i.e; M_z = 90N-m. For the convenience of user and to see that the forces are within elastic limit of the elastic body forces are less.

CHAPTER 5

ANALYSIS RESULTS

Results that are obtained from the analysis of the sensor structure by the application of forcesF_x, F_z and moment M_z.

Results of F_x :

Due to the forces F_x and F_y the deflections will be same; hence the deflections are found out only for the forcesF_x and F_z. By the application of force F_x deflection is done more in the beams OA and OC of the skeleton diagram [1]. Deflections due to F_x and the strain variation is shown in the fig. 5.1 to 5.5, where 5.1 & 5.2 shows the stress variation in the F_x varying between S_{min}= .44 x10^{-5} N/mm^2 and S_{max} = 15.778 N/mm^2. In fig. 5.3, other cross sectional beam the stress variation is found with values S_{min}= .66x10^{-3} N/$mm^2$and S_{max} = .00598 N/mm^2. Fig. 5.4 shows the graph that is plotted for stress variation along the cross sectional beam length. Fig.5.5 is meshing diagram of sensor.

Results of F_z:

The stress variation along the cross elastic beams are shown in the fig. 5.6 to 5. 11. The S_{min} =0 and S_{max} = 6.288 in fig. 5.6, in 5.7 the S_{min}=0.005752, S_{max}=10417, SMXB = 14588. In the fig. 5.8, stress variation along the y direction is S_{min}= .29x10^{-5}, S_{max}= 8.146 and SMXB= 11.456. Fig. 5.9 shows the top view of the deflection due toF_z. In the fig. 5.10, the stress along the central support beam is shown with varying stress of S_{min}=0.63x10^{-3} , S_{max}= 0.005704, SEPC= 29.795. Fig. 5.11 shows the variation of stress along the beams i.e.; cross sectional beams due to the force F_z.

Results of M_z:

Fig. 5.12 and fig. 5.13 shows the front and isometric view of the deflection in the sensor beams due to the moment M_z. Here the stress is varying in vertical beams between S_{min}=.312x10^{-6} and S_{max}= 1.341 and SEPC = 2.214.In the fig. 5.14, stress variation along horizontal beams is as follows. S_{min} = .621x10^{-4}, S_{max}= .559x10^{-3} and SEPC = 24.394

These are the values for the stress variation along the beams for F_x, F_y and M_z.

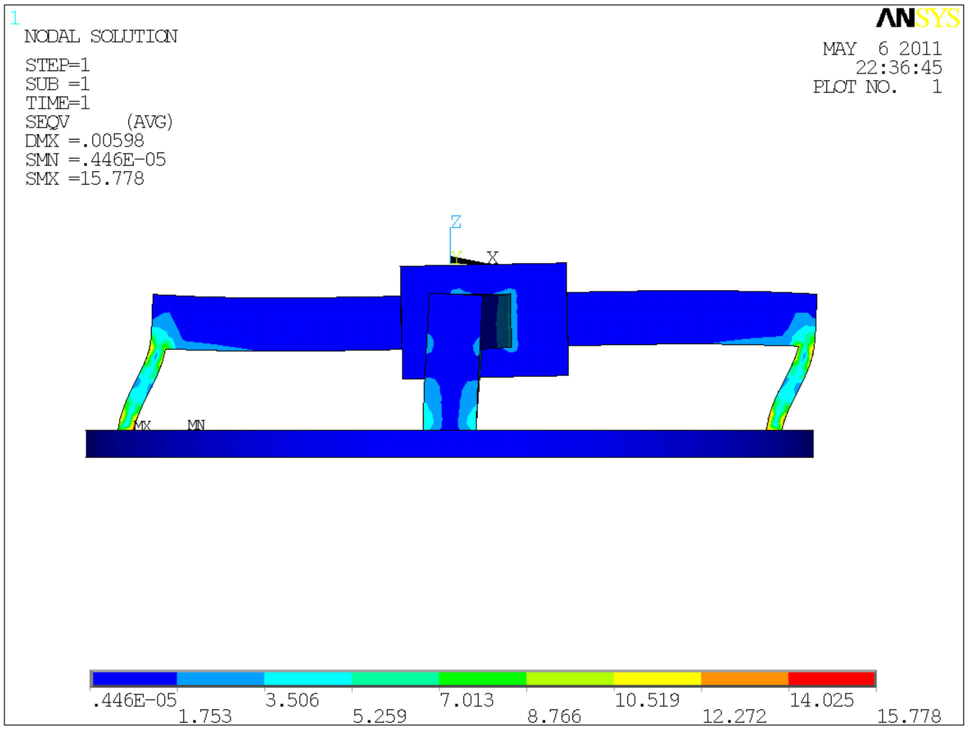


Fig. 5.1 Deflection in the elastic body due to the force F_x front view.

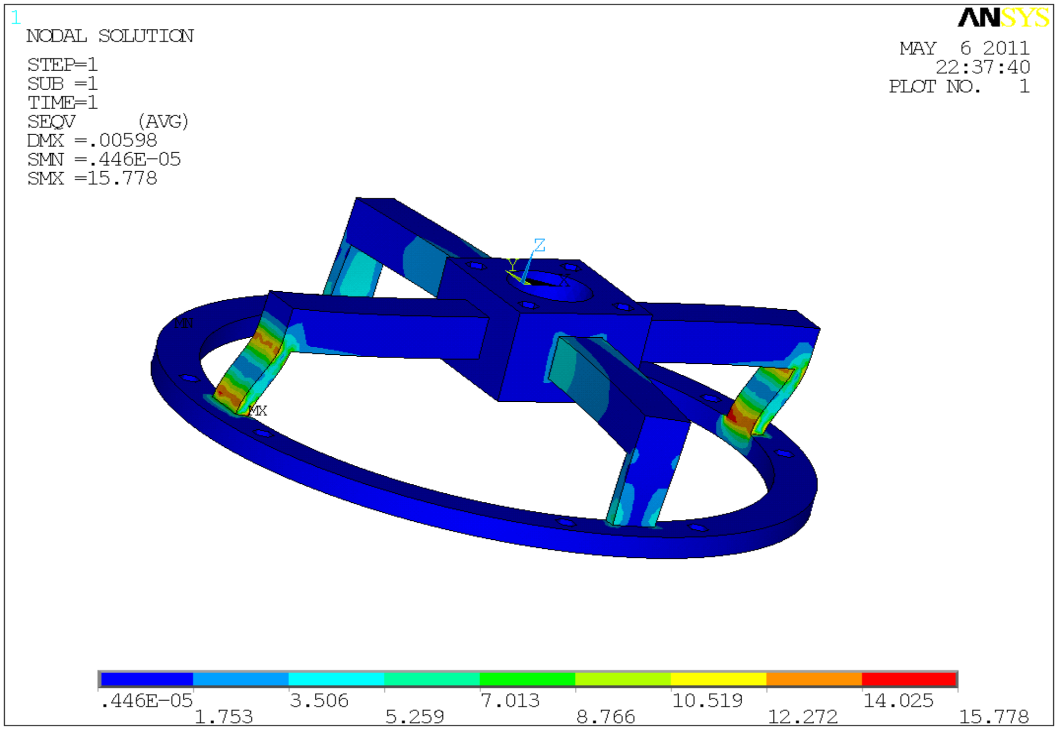


Fig. 5.2 Isometric view of the stress deflections due to F_x

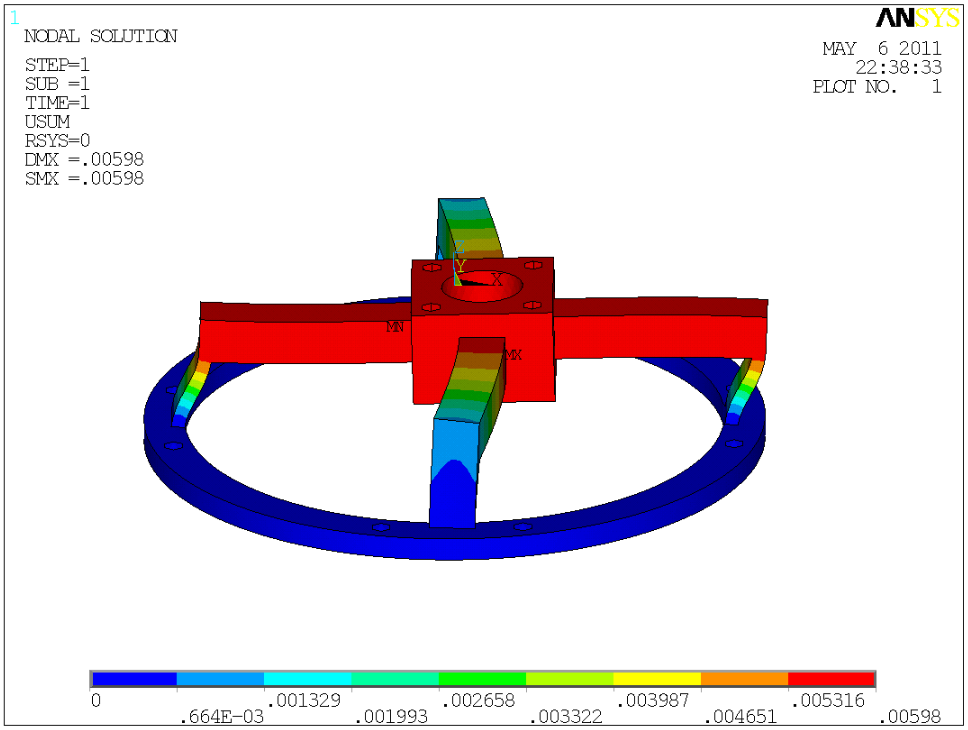


Fig.5.3 Stress variation and deflection due to F_x.

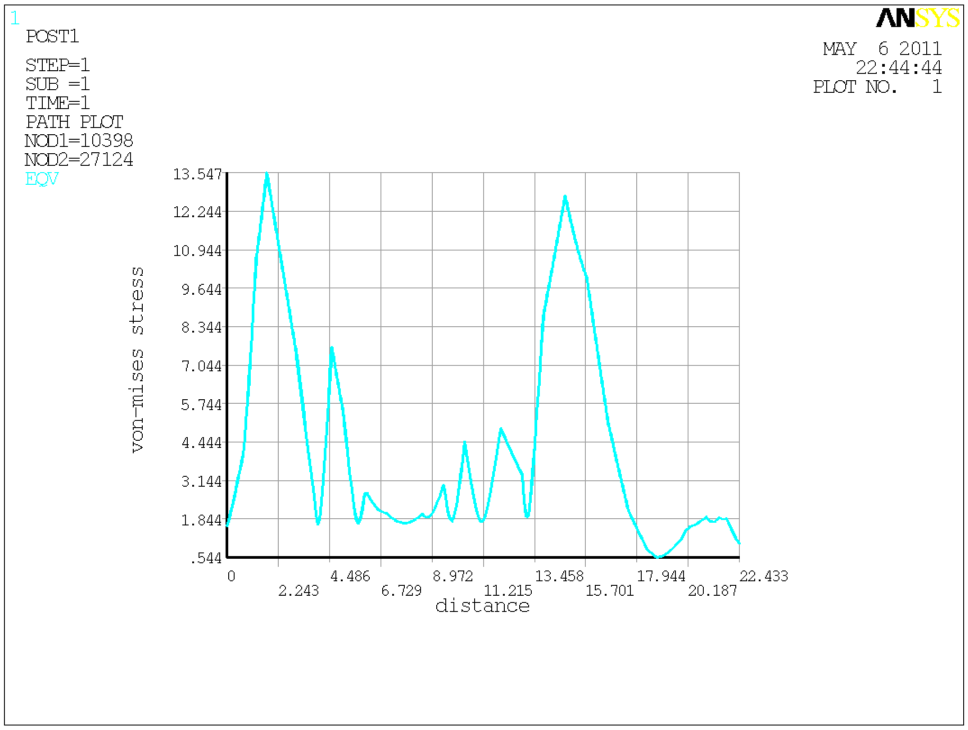


Fig. 5.4 Variation of stresses along the cross elastic beam.

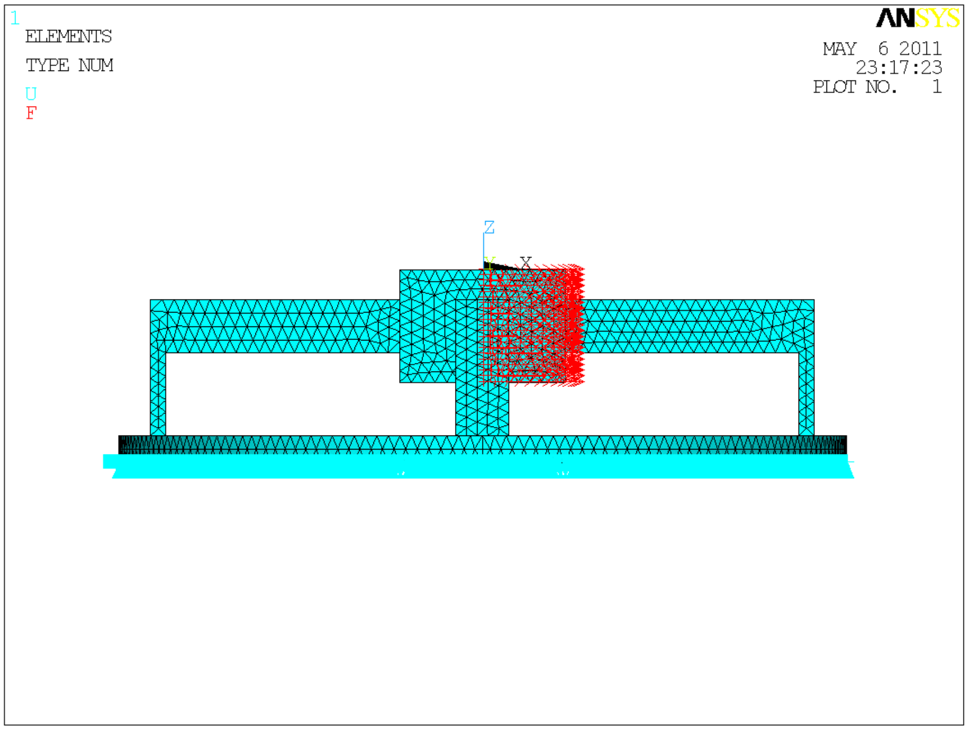


Fig. 5.5 Meshing figure of sensor

Results for force F_z

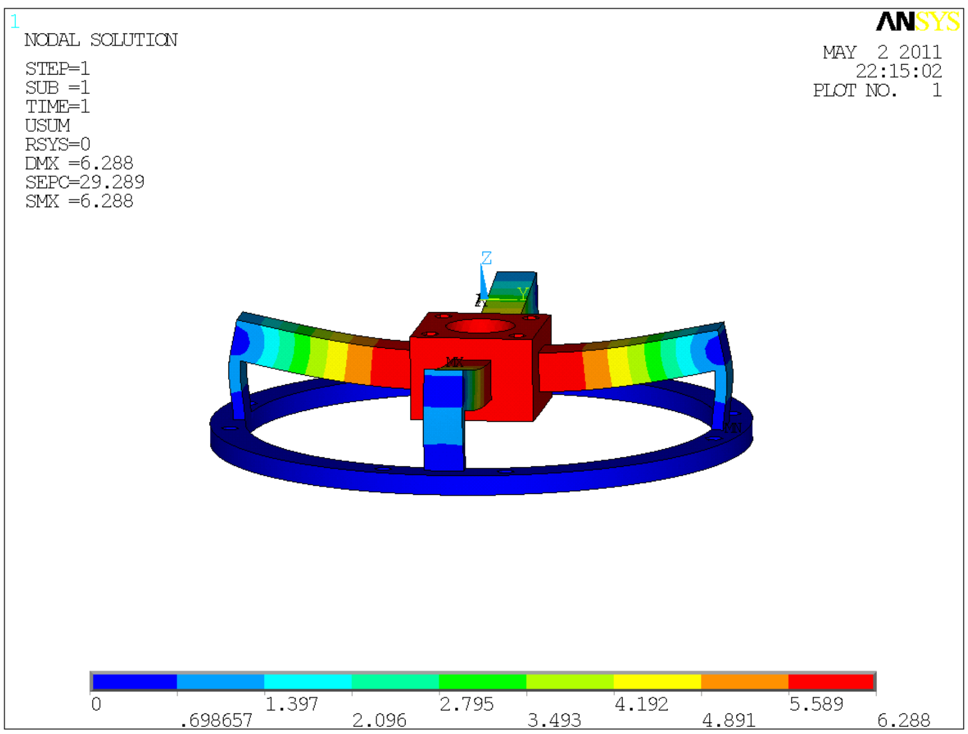


Fig. 5.6 Stress variation along the beams due to F_z.

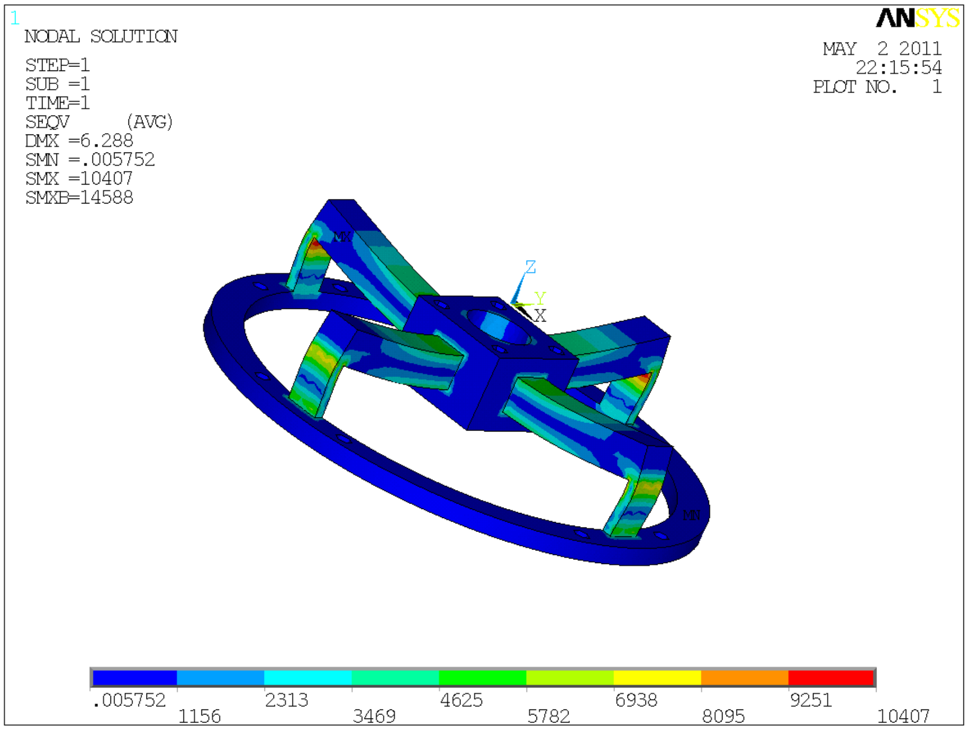


Fig. 5.7 Isometric view of stress variation due to F_z.

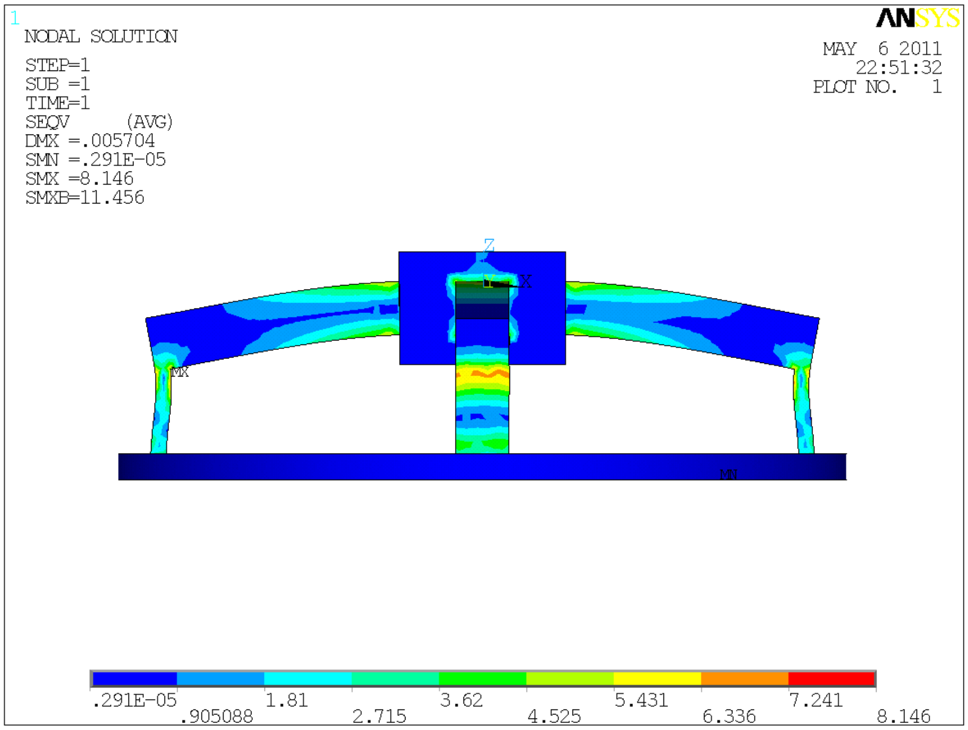


Fig. 5.8 Front view of the sensor structure due to F_z.

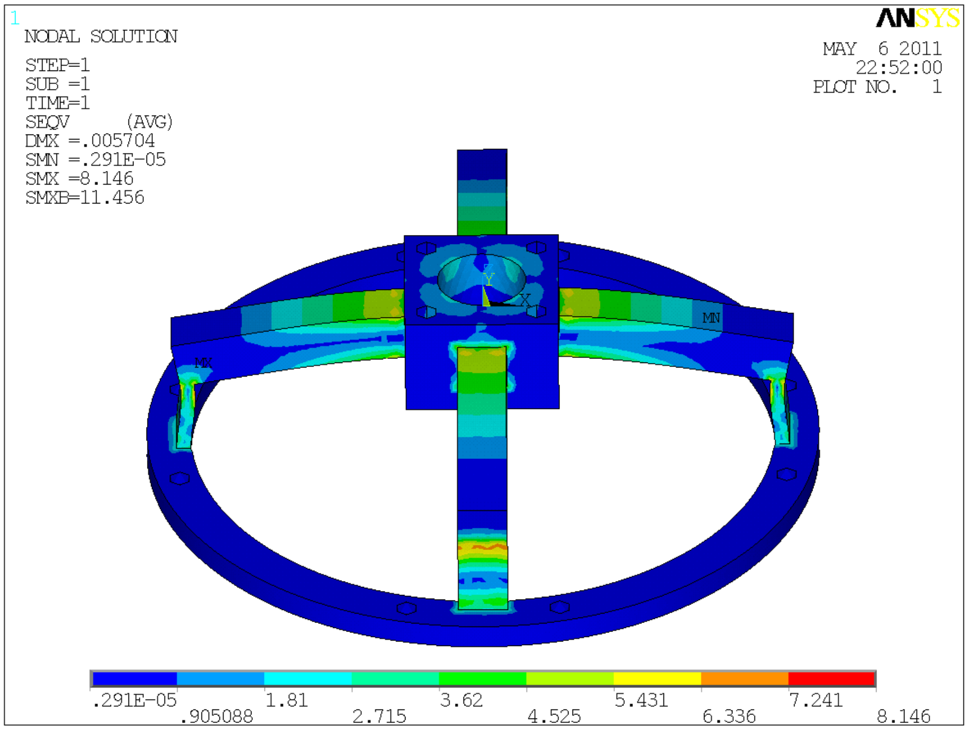


Fig. 5.9 Top view of stress deflection due to F_z.

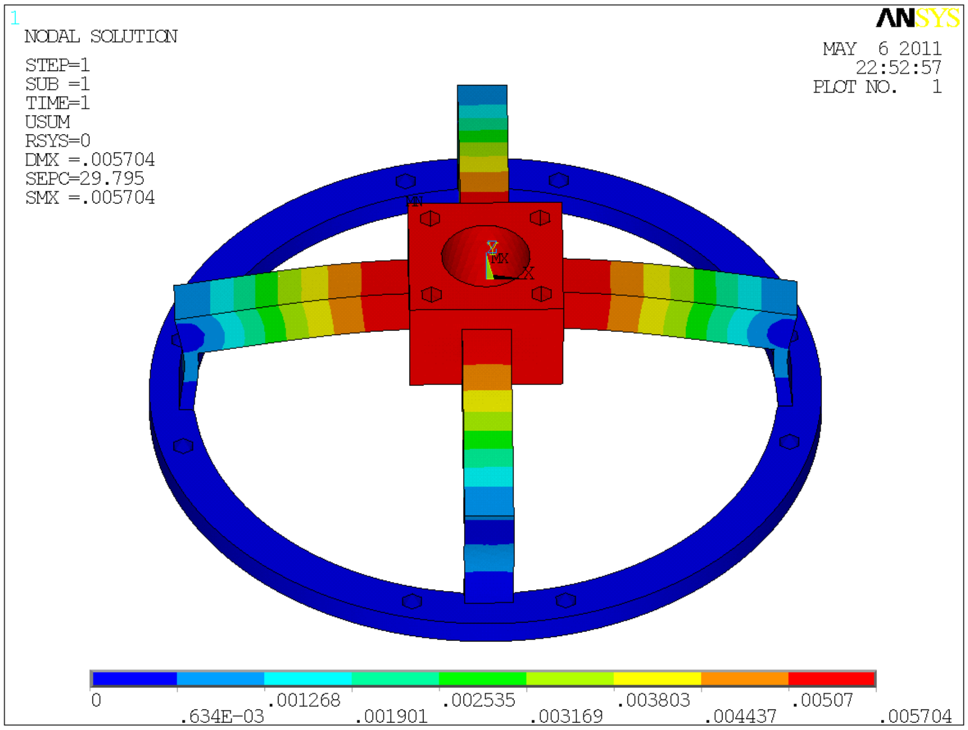


Fig. 5.10 Top view with the stress values along the beams for F_z.

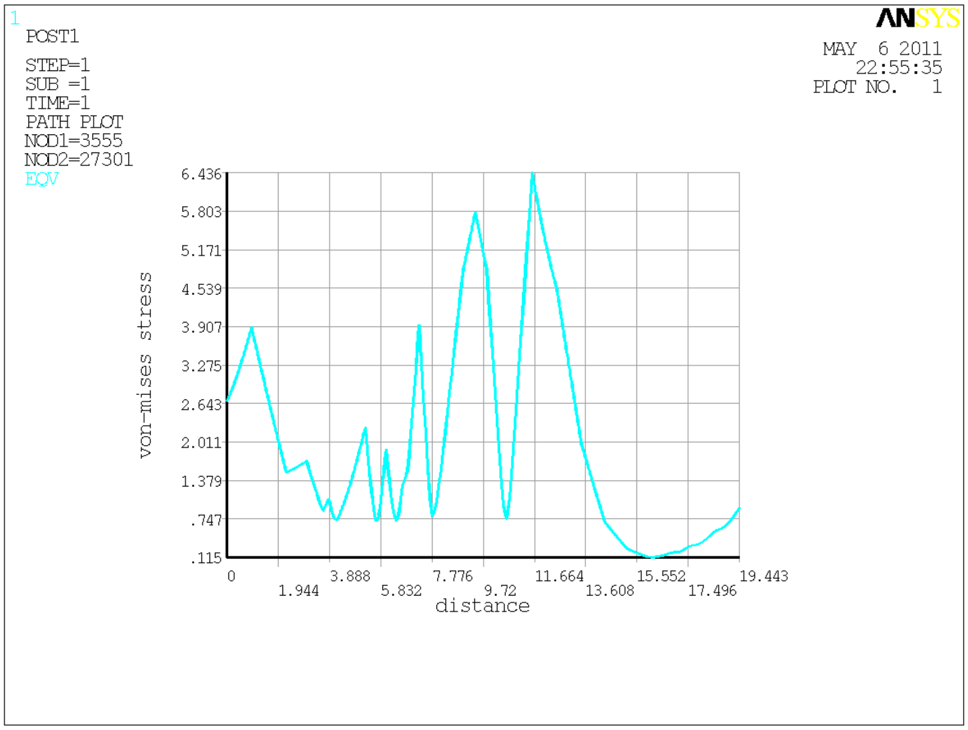


Fig. 5.11 Variation of stress along the beam due to F_z(graph)

Results for momentM_z

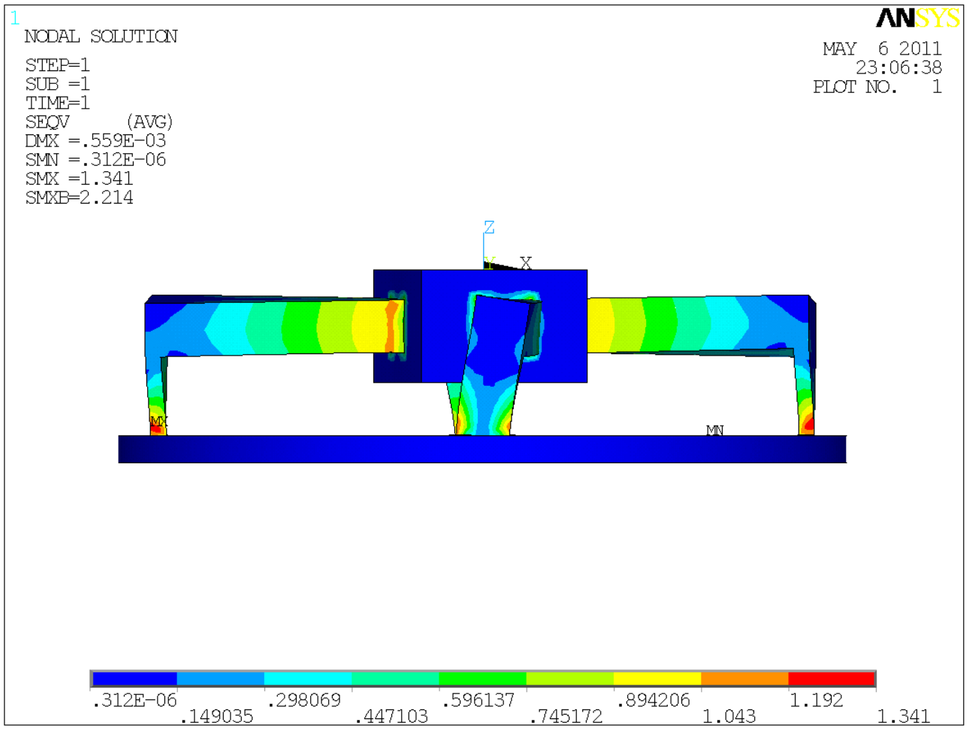


Fig.5.12. Variation of stress along the beams due to M_z.

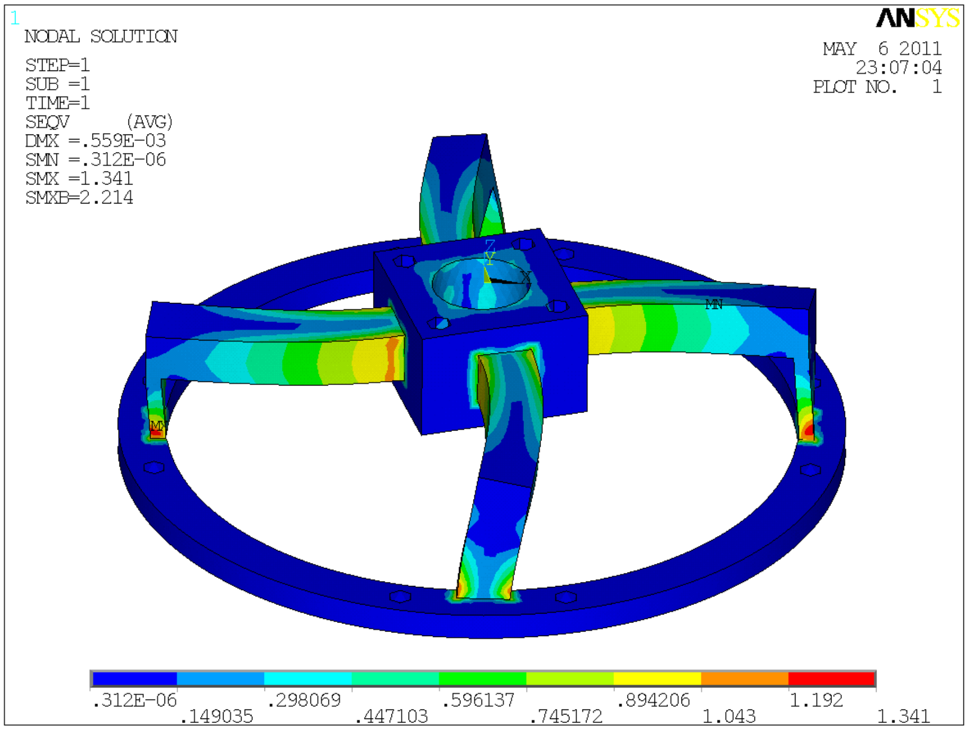


Fig. 5.13 Isometric view of the sensor for variation of stress due to M_z.

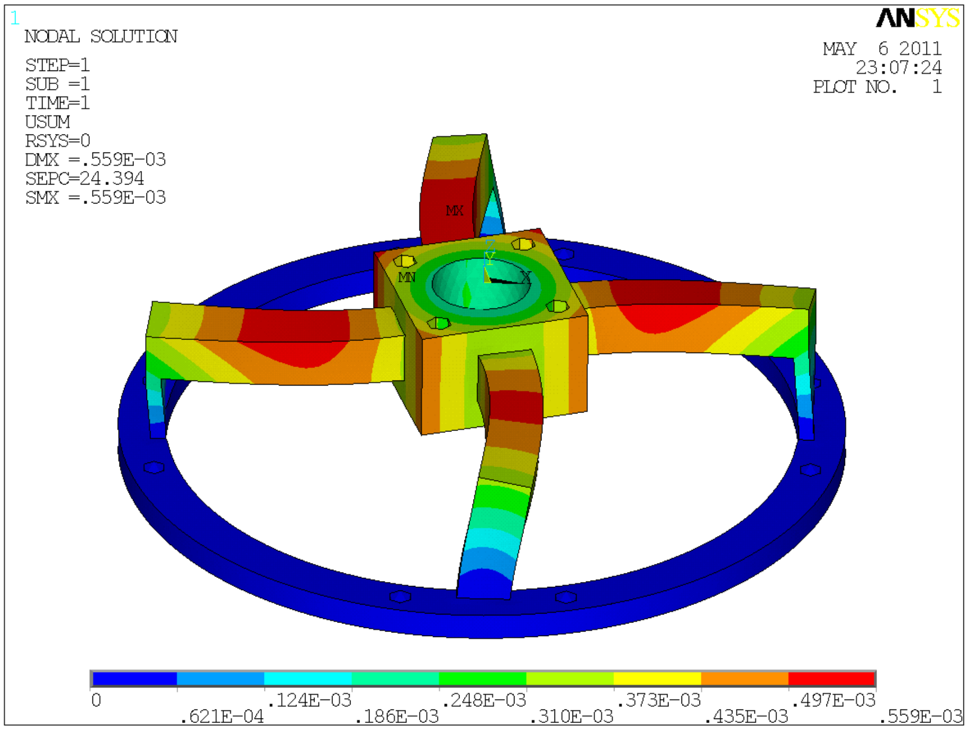


Fig. 5.14. Stress deflection along the beams by M_z.

CHAPTER 6

CONCLUSIONS & FUTURE SCOPE

Conclusions:

1. A new multi-dimensional force sensor is designed here.
2. The variations of stress along the beams are found out and graphs are plotted.
3. To find the whether the design is valid, practical values are found out by doing the experiment getting values of all strain gauges and comparing it with the theoretical values we get the error occurred.
4. Here we have developed a mechanical structure for force sensor and it is analyzed by FEM software ANSYS. Hence it is analyzed that the force is with in elastic limit. Max. Stress points are found out and the strain gauges will be placed in respective places.

Future Scope: The cost of 4 DOF force/torque sensor is low in cost compared to 6 DOF force/torque sensor, it can be made much easier than the present one by reducing its size, which can be attained by reducing the no. of strain gauges glued. It will reduce the cost of commercial force/torque sensors.

CHAPTER 7

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